ESTCP
Cost and Performance Report

(MR-201233)

Demonstration of ROV-based Underwater Electromagnetic Array Technology

March 2017

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The objective of this project is to evaluate innovative technologies required for deploying underwater electromagnetic induction (EMI) sensors from remotely operated vehicles (ROVs). The integration of these platforms, highly accurate navigation and control systems, and a high-resolution electromagnetic array can overcome limitations of current diver-deployed, towed, and unmanned integrated underwater ordnance systems.

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ACRONYMS AND ABBREVIATIONS

AUV	Autonomous Underwater Vehicles
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CH	Channel
CST	Conductivity, Salinity, Temperature
DC	Direct Current
DoD	Department of Defense
DVL	Doppler Velocity Log
E	Easting
EOD	Explosive Ordnance Disposal
EM	Electromagnetic
EMI	Electromagnetic Induction
EMF	Electromotive Force
ESTCP	Environmental Security Technology Certification Program
FA	False Alarms
FDEM	Frequency Domain Electromagnetic
FKMNS	Florida Keys Marine National Sanctuary
GUI	Graphical User Interface
GPS	Global Positioning System
HAUV	Hybrid AUV
I	In-phase
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
IVS	Instrument Verification Strip
ISO	Industry Standard Objects
LAR	Launch and Recovery
MFDA	Multi-Frequency Detection Array
MMRP	Military Munitions Response Program
MSK	Minimum Shift Keying
N	Northing
NAS	Naval Air Station
NCS	Navigation and Control System
NOAA	National Oceanic and Atmospheric Administration
OPENSEA	OPEN Software and Equipment Architecture

OPERA	Operating Area
Pd	Probability of Detection
pFA	Probability of False Alarm
Q	Quadrature
QA	Quality Assurance
QC	Quality Control
ROV	Remotely Operated Vehicles
RMS	Root Mean Square
RTK	Real Time Kinematic
SBAS	Satellite-Based Augmentation System
SNR	Signal to Noise Ratio
SOP	Standard Operating Procedure
TOI	Target of Interest
UI	User Interface
USBL	Ultra Short Baseline
UUV	Unmanned Undersea Vehicle
UXO	Unexploded Ordnance

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EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

The overarching goal of this demonstration project was to evaluate innovative technologies required for deploying underwater electromagnetic induction (EMI) sensors from remotely operated vehicles (ROVs) in order to overcome limitations of current diver-deployed, towed, and unmanned integrated underwater unexploded ordnance (UXO) detection systems. The tests and demonstrations reported on here constitute the first for a tightly integrated ROV and EMI technology for UXO operations. We began our study with graduated and systematic testing in laboratory tanks and pool environments in New Hampshire, then controlled harbor sites in Massachusetts and Florida, and then demonstrated the fully integrated technology at open water test sites we established in North Carolina and Florida. Here we primarily report on our final demonstration of the technology, but results from our earlier work and engineering trials are provided in an interim report available from ESTCP.

TECHNOLOGY DESCRIPTION

For this demonstration, we integrated and implemented a hybrid autonomous undersea vehicle (HAUV) designed to provide a stable and mobile geophysical sensing platform for seafloor investigations. The HAUV combines a vector-controlled propulsion system with a highly accurate inertial navigation and control unit to provide a number of controlled autonomous or manual survey missions. These include waypoint navigation, bottom following, and station keeping - all of which enable important aspects of maneuverability and positioning control in close proximity to the seafloor. This ROV platform was integrated with the multisensor frequency-domain digital EMI array (MFDA). This array employs three differential (quadrupole) receivers and acquires frequency-domain in-phase and quadrature-phase magnetic field data at discrete frequencies over the band from 400 Hz to 40 kHz.

The inertial navigation and control system used on the ROV allowed for the robust detection of small munitions (60 mm diameter) under varied conditions by providing accurate sensor positioning while executing autonomous search modes in water depths of up to 20 m.

DEMONSTRATION RESULTS

In April of 2015, we established a temporary UXO test grid site on the seafloor within the Florida Keys National Marine Sanctuary approximately 7 km south of the Boca Chica Key Naval Air Station in the lower Florida Keys. The test site was surveyed and prepared by divers, including the installation of 30 m X 40 m target grid with 23 UXO test items. The demonstration we conducted was the first that we know of in which a fully marinized multi-sensor EMI array on an ROV system successfully performed controlled data collection maneuvers close to the seafloor. Despite the preliminary nature of our assessment, we were able to evaluate the prospects and potential challenges for directly transitioning and implementing the system and related procedures for operational use in MMRP production environments

We successfully demonstrated a number of functions of the integrated ROV-EMI sensor system, including (i) bottom seabed following to within ±10 cm at a commanded 50 cm standoff, (ii) system station keeping to within ±20 cm of a commanded target location, (iii) waypoint navigation to within <1% of distance travelled and line following to within 75 cm at all times, and (iv) UXO target detection with signal-to-noise ratios >20 dB and localization accuracy within 70 cm.

In addition, we conducted assessments of the cost and logistical complexities for potential deployment and operations of the technology. Projected daily rates of approximately $7,500 for the integrated demonstration system (including an ROV operator) lead to considerable savings relative to deployment of an EOD-trained dive team searching the seafloor for UXO. Estimation of incurred labor and equipment costs estimated during survey mode operations yields a 100% real coverage costs of approximately $600/acre. We assessed potential cost savings through the use of this technology for a particular UXO site study where 500 survey contacts required reacquisition and further investigation. In this case, the ROV-EM system reveals as much as a 60% cost savings relative to conventional diver-based methods. Previous assessments have identified as many as 420 underwater ranges at over 120 different military sites, comprising approximately 10 million acres of marine or lacustrine environment potentially contaminated with UXO. Of these 420 sites, it projected that 100 or more contain water depths that prohibit the use of towed geophysical survey systems or EOD divers. Where sites are shallow enough for EOD divers (<30 m) to conduct visual or handheld detector surveys, dives are highly constrained in duration and activity by strict health and safety regulations. If even as few as 1/3 of the existing sites can utilize ROV-based EM sensing, there is great potential cost savings in addition to improvements in diver health and safety. Dives generally require teams of five or more specialists and nominally cost $2,000 to $3,000 per dive. Our ROV-based EMI can be deployed with as few as three operators (one helmsman, one analyst, one technician) for $600-$800 per dive - thus reducing the estimated daily cost (assuming ~10 dives/day) from $25,000 to $7,000 (~70% reduction).

IMPLEMENTATION ISSUES

The demonstration was divided into three distinct types of applications or survey missions: 1) local area UXO detection search (0.5 to 2.5 acres at a time), 2) close-in anomaly characterization (full coverage dynamic characterization and localization), and 3) reacquisition and cued data collections. The ROV-EMI system was successful and effective at completing each mission type, with the close-in anomaly characterization being the most effective application of the technology.

While the demonstrations of this ROV-based EM technology showed effective surveying over moderately sized (1-2 acres) areas, larger areas proved more challenging. A clear limitation of the ROV-EM system we demonstrated in terms of survey coverage efficiency is due to the limited size of the EM sensor array used. Full coverage over a site requires 1 transect every 50 cm. Therefore, at an estimated 1 knot (0.51 m/s), our estimated survey coverage efficiency is approximately 4.4 hours per acre (requiring 8192 m of linear line transect surveying). Including turnaround time and daily IVS and related QA checks, this is equivalent to approximately 1.5-2 acres per day. The survey efficiency simply scales linearly with array survey coverage swath width or areal coverage planned. Thus, an array two meters wide would likely cut the current survey time in half and increase the production rate to 3-4 acres per day.

1.0 INTRODUCTION

Current methods for detecting and characterizing underwater ordnance rely heavily on explosive ordnance disposal (EOD)-trained divers for visual inspection and handheld metal detector surveys. These dive teams are highly constrained in duration, depth, cost, and activity by health and safety regulations. While autonomous underwater vehicles (AUVs) provide an alternative, those currently available for marine munitions response operations require well-trained operators and do not allow for real-time awareness of the seafloor environment. Additionally, the hydrodynamics and propulsion configurations of commercial AUVs preclude hovering for cued interrogation and very slow or adaptive operation at, or very near, the seafloor. Therefore, we set out to evaluate innovative technologies required for deploying underwater electromagnetic induction (EMI) sensors from remotely operated vehicles (ROVs). The integration of these platforms, highly accurate navigation and control systems, and a high-resolution electromagnetic array can overcome limitations of current diver-deployed, towed, and unmanned integrated underwater ordnance systems. Specifically, ROV-based sensing enables the positioning of array-based sensors directly over targets of interest.

1.1 BACKGROUND

At many sites, ROV-based EMI sensing may reduce the cost and health-and-safety burden currently placed on diver surveys while enhancing the overall awareness of underwater UXO environments from high quality EMI data collected in conjunction with supporting visual and acoustic sensor modalities. Successful deployment of ROV-based EMI sensing will demonstrate 1) a close and well-controlled standoff from the seafloor, 2) real-time operator situational awareness and dynamic repositioning of sensor arrays, and 3) implementation of EMI sensor arrays capable of detecting and discriminating small munitions to greater depths than manned, surface-towed, or fully autonomous sensing systems. Although the performance of the system depends on the type of environment, bathymetry and bottom characteristics, currents, and target type and distribution, this demonstration project showed that the system can provide critical capabilities of precise data collection, sensor positioning, and terrain following, resulting in high probabilities of detection of underwater munitions.

1.2 OBJECTIVE OF THE DEMONSTRATION

The primary objective of this demonstration was to quantify the performance of an integrated EMI array sensor, precision navigation and control system, and hybrid AUV/ROV platform through testing in a realistic underwater environment. Performance was assessed through analyses of the integrated EMI array, position, and attitude data collected during execution of multiple underwater unexploded ordnance (UXO) detection operations: 1) wide area coverage, 2) anomaly characterization, and 3) anomaly reacquisition. Another objective was to quantify improvements in UXO detection using precise control by comparing EMI sensor data registered with positioning methods of varying degrees of accuracy. We were able to meet many of the objectives and prove how ROV-based EMI system deployment can be effective in local area search scenarios. The most difficult objective to meet was the wide area search mission as waypoint and/or line following capability was only as effective as the positioning and control methodology used (in our case 0.5-1% of distance traveled, thus limiting the accuracy of positioning over large areas).

1.3 REGULATORY DRIVERS

There are no explicit regulatory drivers or considerations associated directly with this preliminary demonstration. All demonstration activities were conducted in waters regulated by federal and state (Florida) laws and outside of any military areas or regulated by special munitions contamination provisions. The Department of Defense (DoD) is responsible for assessment and remediation of numerous munitions sites, many containing in-water areas, in the United States. When the transfer of responsibility to other government agencies or to the civilian sector takes place, the DoD lands fall under the compliance requirements of the Superfund statutes. Section 2908 of the 1993 Public Law 103-160 requires adherence to Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) provisions.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

In this project, we demonstrated an EMI sensor integrated with an ROV platform capable of accurate positioning and control. The ROV and positioning control system combines the Dolores Hybrid AUV (HAUV) 1000 with the commercial Balefire navigation and control system developed by Greensea Systems. The primary EMI sensor payload technology is the Multisensor Frequency-domain Digital Array (MFDA) modified by White River Technologies for underwater UXO detection and tightly integrated with the high performance AUV control system, in addition to auxiliary sonar and environmental sensors (i.e., high-definition video and imager, electrical conductivity, salinity, and temperature).

The HAUV-1000 was originally designed and built by Greensea Systems in 2011. This AUV system, known commonly as "Dolores," is permanently installed on an operations vessel and is equipped with forward-looking sonar, side-scan sonar, a low-grade inertial navigation system, and is powered by two 5.35 kW-hour lithium-ion ($LiFePO_4$) rechargeable batteries. The on-board subsea power management system provides up to 14 continuous hours of operation in ROV mode and over 18 hours in AUV mode. The system was commissioned by Cobalt Marine LLC and is dedicated to marine geophysical survey and archeological salvage operations. As a hybrid system, it provides remote control typical of traditional ROVs using a fiber-optic tether as well as a fully autonomous mission execution with or without the tether. A full autopilot suite provides for higher performance control than is typical with traditional inspection class ROVs by augmenting the remote control operation with waypoint navigation, station keeping, attitude control, precision bottom following, and fly-by-wire joystick features.

The EMI array is mounted directly to the non-metallic ROV structural frame chassis. It is positioned slightly below the ROV to minimize potential standoff distances from the seafloor. The sensor head comprises a 45 cm x 65 cm transmitter and three figure 8–shaped (quadrupole) receiver coils (Figure 1). The three quadrupole receivers form oppositely wound coils (monoloops) that create an equal and opposite electromagnetic field (EMF) from the transmitter on each monoloop coil. This frequency-domain sensor has the advantage of superior control of selection and power in the frequency content of received signals. In marine applications where conduction currents influence the quadrature-phase signal, the FDEM approach provides additional in-phase information that may be important for characterizing targets of interest (Schultz et al., 2011).

EMI array hardware integration was done using a pair of specially fabricated PVC arms attached to the front of the HAUV and to the EM sensor via a pair of fiberglass angle brackets. This mounting configuration provided a stable means of positioning the sensor in front and below the HAUV platform. The location of the array forward of the vehicle enabled viewing of the sensor through the forward HAUV camera. Positioning of the sensor below the HAUV enabled the sensor to be stationed near the bottom, or even on the bottom, while maintaining HAUV bottom standoff of greater than 30 cm, the height required by the DVL for maintaining bottom lock.

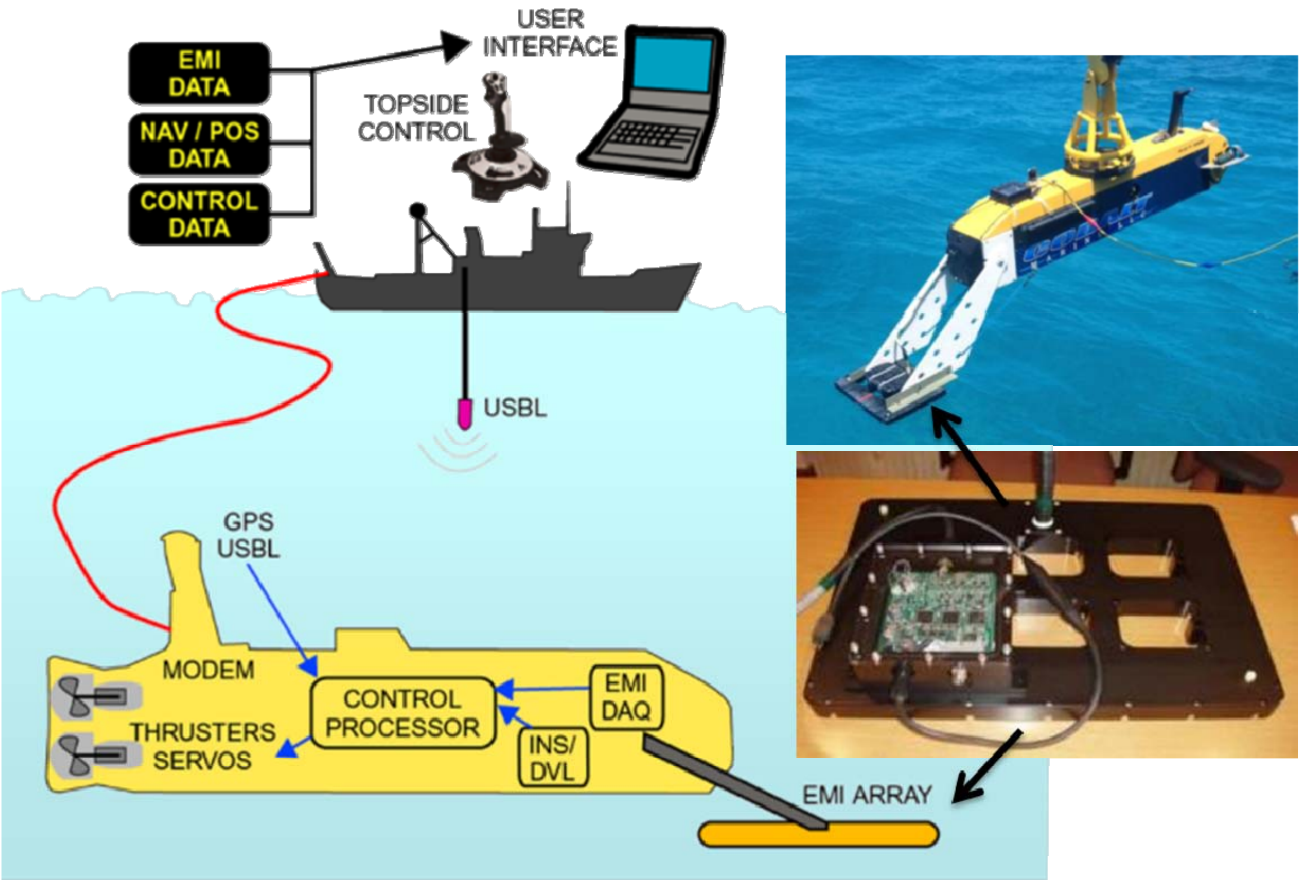

Figure 1. Diagram of Topside and HAUV Sensors and Processing Components.

Our navigation system is based on a high-performance inertial core sensor, mounts to any underwater vehicle, and requires relatively little integration. It fuses the data from aiding sensors with the core inertial measurements and continuously calculates vehicle position and orientation. Topside, the system control graphical user interface (GUI) communicates with the subsea sensors through the ROV fiber optic thin line tether. Mission planning capabilities, including the creation and editing of waypoints to follow during wide area coverage, resided on the navigation and control GUI panels: Mission planning modules, HAUV real-time camera display, sonar data, as well waypoint maps, system status and configuration, and the EM data display - as shown in Figure 2.

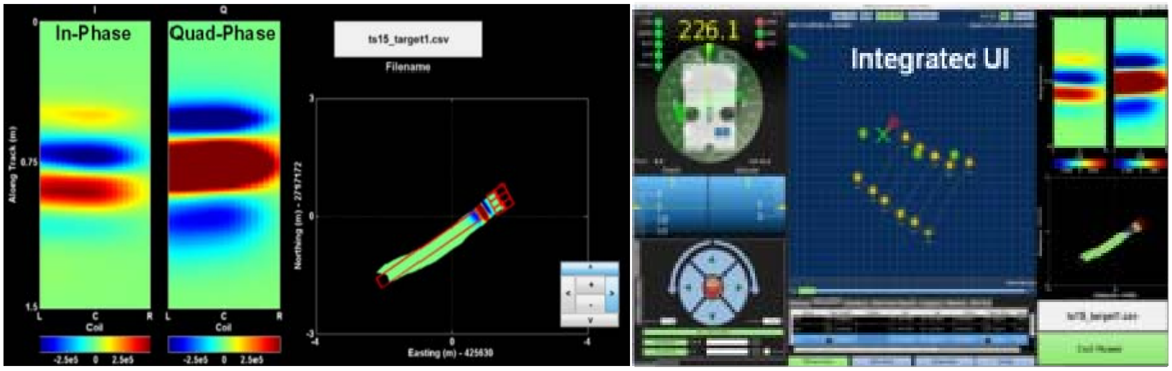

Figure 2. The Standalone MFDA Data UI (left figure) Showing the In-phase and Quad-phase Color Mapped Array Waterfall Plots (left-side panel).

Data anomalies are interpolated across the array (Left "L," Center "C," Right "R") and flow from top to bottom as the system moves along the seafloor. The quad-phase map is also "painted" over a map display (right-side panel) and standard pan and zoom features are accessible to the operator. A data filename and logging UI tool are also provided. This interface was integrated as a module into the openSEA workspace and is shown in the right figure on the rightmost panel.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The ROV-based EMI technology has particular advantages over EOD-trained divers equipped with handheld detectors or EM or magnetometer arrays towed from surface vessels. Divers are highly constrained in terms of the mobility, depth, and duration during dives due to strict health and safety regulations, as well as physics. Towed systems, as well as fully autonomous unmanned undersea vehicles (UUVs), place sensors 2-5 m above the sea floor and thus restrict detection capabilities to large UXO only. The ROV-based EMI technology we demonstrated is capable of following the bottom at 30-50 cm standoff with very tight control (to within +/- 15 cm). Because signal levels drop off quickly with range from a target, it is critical to accurately and precisely position the sensor in varying conditions. Real-time operator situational awareness and dynamic repositioning capability afford the operator both a dynamic mapping mode and a detailed reacquisition or static characterization mode with data collection over suspected targets.

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3.0 PERFORMANCE OBJECTIVES

The performance objectives (Table 1) were focused on demonstration of precise system positioning and control required for execution of UXO detection and characterization missions. The functions we demonstrated include station keeping, bottom following, and waypoint navigation while achieving correlated EMI data quality metrics during area coverage and mapping and detailed area or reacquisition surveys.

Table 1. Performance Objectives

Performance Objective	Metric	Data Required	Success Criteria
Quantitative Performance Objectives			
Bottom Following Accuracy	Average error between desired altitude and true altitude of system, standard deviation of true system altitude	• Beginning and End waypoint coordinates • Desired altitude • Altitude reports from the navigation and control system	$\Delta A < 0.15$ m $\sigma A < 0.15$ m
Station Keeping Accuracy and Precision	Average error and standard deviation in northing, easting, and altitude between true position and desired position of the system Average error and standard deviation in heading, roll, and pitch	• Anomaly location (desired position), within 10 cm • Desired altitude • Desired heading, roll, and pitch • Position and orientation reports from the navigation and control system	ΔN and $\Delta E < 0.35$ m σN and $\sigma E < 0.35$ m $\Delta A < 0.15$ m $\sigma A < 0.15$ m $\Delta H < 1$ degree $\sigma H < 2$ degree $\Delta R < 1$ degree $\sigma R < 2$ degree $\Delta P < 1$ degree $\sigma P < 2$ degree
Waypoint Mission Control	Average error in distance between line defined by waypoints and recorded position Standard deviation of error between linear path followed and recorded position	• Beginning and End waypoint coordinates (true line position) • Position reports from the navigation and control system and calculated deviations from a best-fitting straight line path to the points along travel	$\Delta D = (\Delta N^2 + \Delta E^2)^{0.5}$ $\Delta D < 1.5\%$ distance travelled $\sigma D < 0.5$ m
Detection of all munitions greater than 60 mm	Signal to Noise Ratio (SNR) of signal produced by munition in EMI sensor to noise in EMI sensor	• Signal received during anomaly interrogation • Noise estimate during anomaly interrogation • Position reports from the navigation and control system	SNR > 9 dB Pd > 0.95 (assuming a nonfluctuating target and Gaussian noise a 0.95 Pd at 9 dB corresponds to a pFA of approximately 0.01)
Detection Location Accuracy and Precision	Average error in northing and easting between true position and estimated target position	• MFDA data • Navigation data • True Target Locations	ΔTN and $\Delta TE < 1.0$ m σTN and $\sigma TE < 1.0$ m
Qualitative Performance Objectives			
Ease of use	Operator observations	• Field notes recorded during setup and testing	Ease of use comparable to alternate standard marine surveying procedures
Mission Assisted Autonomy	Operator observations	• Comparisons of manual and automated control	Value of assisted autonomy functions
Integrated System Stability	Operator observations	• Time and effort spent trimming system	Valuation of time and effort to stabilize

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4.0 SITE DESCRIPTION

The demonstration site we selected was within the Florida Keys Marine National Sanctuary (FKMNS), about 7 km south of the Boca Chica Key and approximately 250 m north/northwest of Middle Sambo Key on the southern part of the West Florida shelf area off the Lower Florida Keys. The FKMNS site is administered by the Department of Commerce National Oceanic and Atmospheric Administration (NOAA) and is managed by both NOAA and the state of Florida's Board of Trustees of the Internal Improvement Trust Fund through the Florida Department of Environmental Protection.

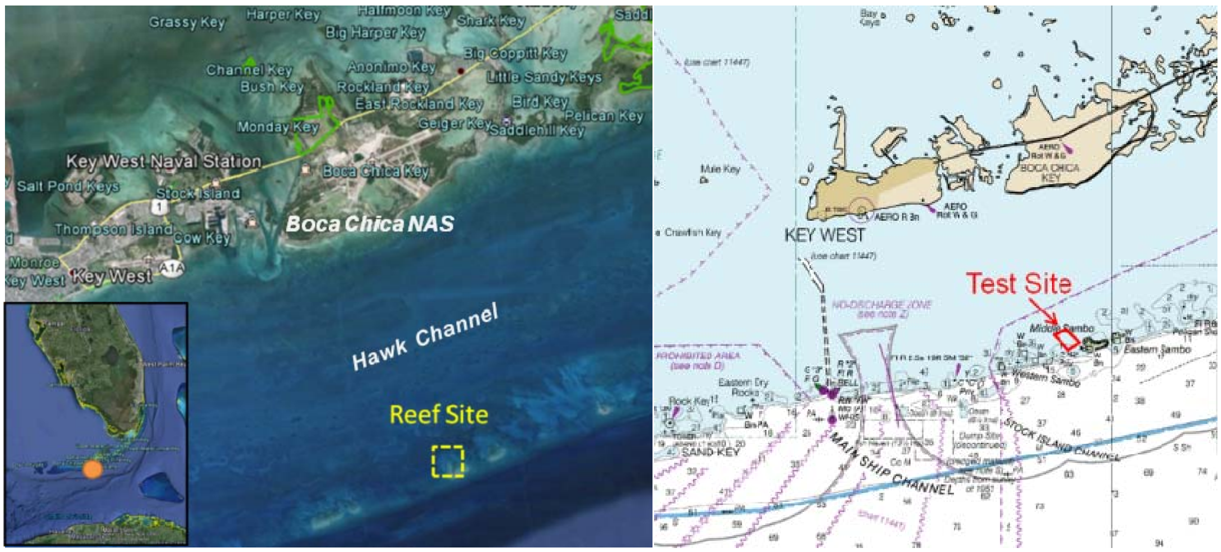


Figure 3. The General Study Area is within the Southern part of the Hawk Channel, ~7.5 km South of the Boca Chica Key, Between the Stock Island Channel and Eastern Sambo Ecological Area.

4.1 SITE LOCATION AND HISTORY

Our specific study site area is primarily used for boating and diver recreation on the adjacent Sambo reefs and wreck sites and for fishing. Previous surveys have established spar buoy anchor points and other sea surface or sea bottom fiducial markers to use as survey baselines. The use of these sites allowed us to configure, test, and assess system validation results from realistic conditions without incurring logistics and DoD intrusive site investigation expenses that would be required for demonstration at a live site during this stage. The study site is relatively flat and featureless in contrast to adjacent areas that have some varying relief and benthic conditions (sea grass, mixed carbonates, hard bottom). These areas have been identified and logged during preliminary ROV-EM surveys, as well as from numerous recreational, research, and salvage diver logs from this area. The southern portion of the site area has been surveyed extensively by dive teams during dive operations, benthic habitat studies, and ecological surveys. This part of the site contains undisturbed sands and hardbottom with shell and coral distributed throughout in water depths extending between 17 and 44 feet (5-14 m).

Both natural and cultural events have shaped this area of the Lower Keys. The site area has a rich maritime and ecological history, including heavy use as a trade route in the 17th century, primarily by Spain. In more recent times, the Lower Keys became an attraction for visitors, divers, fisherman, and explorers. Beginning in 1957, environmental conservationists began working to preserve offshore areas around the Keys by establishing state parks and marine conservation areas, including the establishment of the Florida Keys National Marine Sanctuary.

Over recent history, storm systems have arguably played the largest role in terms of acute events that affect the sea bottom in the area. This has included significant hurricanes in 1966 and 1992, as well as numerous tropical storms over the past few decades.

4.2 SITE GEOLOGY

The general area encompasses offshore areas south of Boca Chica Key between the Hawk Channel and outer reef on the edge of the Florida Straits. This area is part of the Florida plateau, a large carbonate platform composed of varying types of marine sediments, which has been an important research site for classic studies in carbonate sedimentology dating back to Vaughn [1915; 1916] and remains one of the most popular sites for continued study. Sediments in this area are characterized by submarine mega-ripples, small sand dunes, and tidal bars. Some submarine dunes overlie oolite and are primarily composed of Halimeda sands (Shinn and Japp, 2005). Tidal channels between the sand tidal bars are often populated with sea grasses. We did not find the Pleistocene bedrock exposed in any low areas in the tidal channels, but it is assumed that the bedrock is exposed where thin layers cover low areas just outside of our study area. A number of geotechnical and geophysical studies have detailed the sediments and morphology of the seafloor environment in this area (e.g., Lidz et al., 2003; Brandes, 2001; Incze, 1998; Lidz et al., 1997; Shinn et al., 1990).

4.3 MUNITIONS CONTAMINATION

Although our test area was not specifically selected based on proximity to known munitions areas, UXO contamination has been cited in the area. DOD currently maintains the largest unencumbered airspace for training on the East Coast. Large portions of the offshore (and some onshore) areas around the Lower Keys are part of an active over-ocean multiuse training area. The Naval Air Station (NAS) Key West manages multiple areas in the Key West Range Complex and operates with only a few environmental restrictions near the Dry Tortugas area. The NAS outlines specific training activities and danger zones, including aerial gunnery ranges, bombing and strafing target areas, and mine fields and special operations training sites. There are also a few onshore military facilities in the Keys, but none are known to have a munitions contamination issue.

Surveyors and salvage crews working in the area have recovered inert practice bombs, fragmentation, and numerous munitions remnants from the Quicksands areas west of the Marqueses Keys. Commonly found items in the area are AN-MK-5 and AN-MK-23 practice bomb targets.

5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The conceptual design of this demonstration focused on the collection of high quality EM sensor and navigation data using the HAUV-1000 ROV platform. Specifically, we set out to demonstrate semi-autonomous means of maintaining one or more of the following parameters: altitude, X-Y position, orientation, direction of travel, or speed of travel. The focus was on determining the ability of the integrated ROV-based EMI sensor system to perform these semi-autonomous behaviors applicable to UXO detection and characterization. These behaviors are required to complete three underwater UXO detection missions: 1) areal coverage and mapping, 2) cued anomaly characterization, and 3) reacquisition and persistent station keeping/sensing. Our tests were designed to capture the ROV's navigation and control accuracy and precision and the resulting quality of the EMI data acquired during execution of the semi-autonomous behaviors.

5.2 SITE PREPARATION

Prior to installing a target grid at the site, we worked to develop a simple and straightforward method for deployment that did not overly rely on diver surveying or dead reckoning once on the seafloor. This led to the design of a 30 m x 40 m target grid area within larger north-south transecting profiles. To ensure proper relatively positioning of targets and help to retain accuracy and integrity of ground truth, we utilized a set of anchored seabottom lines to outline the grid. Divers deployed the lines with cement blocks anchoring the corner markers. The target placement along the bounding box lines and crosslines were set and marked. The lines were then fixed to the pre-surveyed corner markers and run along compass dead reckoning orientations to ensure right angles and end-point consistency.

Seeded items included Industry Standard Objects (ISOs; Nelson et al., 2009), ferrous ordnance simulants of different sizes (60 mm to 155 mm), and clutter. ISO objects were the standard 2-inch (Medium) and 4-inch (Large) steel pipe sections normally used as ISOs. UXO simulants consisted of inert simulant munitions from White River Technologies' inventory of munitions test items. Clutter items were acquired from the shipyard and from local archeological surveyors. These consisted of chains, shackles, aluminum plates, and rebar. A composite photograph of the test items used in the target grid is shown in Figure 4.

1 - 60mm Mortar (with fuze)
2 - 81mm M43A1/M49A2 Mortar (no fuze)
3 - Large ISO
4 - 81mm Mortar (with fuze)
5 - 81mm M821A1/M889A1
6 - 81mm M43A1/M49A2 Mortar (no fuze)
7 - Medium ISO
8 - 10" x 10 " Aluminum diamond plate
9 - 81mm Mortar (with fuze)
10 - Medium ISO
12 - Large ISO
13 - 60mm Mortar (with fuze)
14 - Medium ISO
15 - Steel Chain
16 - Steel Chain with Shackle
17 - 105mm Projectile (w/ band and solid tip)
18 - 155 mm Projectile
19 - 90mm Projectile (no widescreen)
20 - 3" Armor Piercing Projectile MK28-A
21 - 105mm Projectile (Blue Training Round)

Figure 4. Photograph and Table of the UXO Stimulants and Other Targets Used.

Prior to establishing the target grid, divers used handheld marine metal detectors to ensure the area was cleared of metallic debris or clutter. Divers installed targets at the prescribed grid locations and performed validation measurements using diver reel measuring tapes and trigonometric survey techniques.

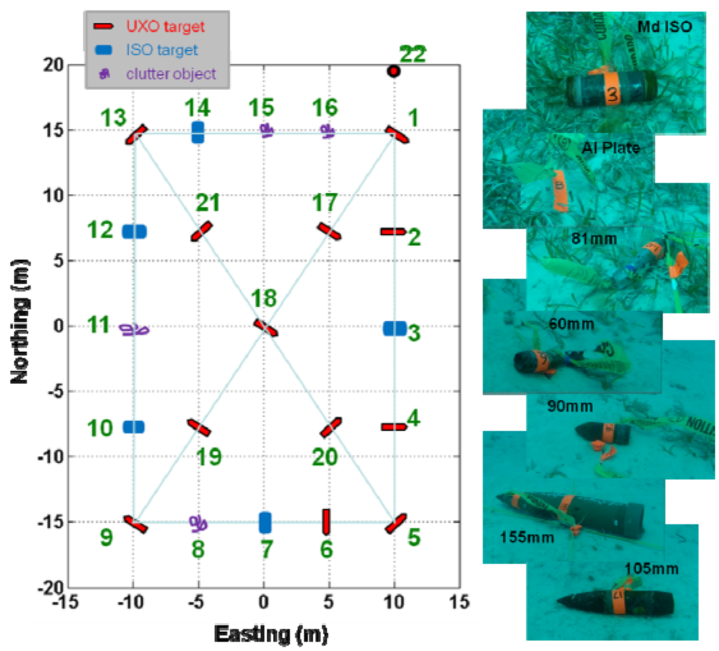


Figure 5. Target Grid Layout with UXO Simulants, ISO, and Clutter Objects Oriented along Perpendicular Transects.

Targets are spaced along grid points and surveyed using the grid corners as a global reference. This set up contains 17 distinct targets, with 12 UXO simulants, 5 ISOs, and 4 clutter objects.

5.3 SYSTEM SPECIFICATION

The complete system used in our demonstration included the multi-frequency EM sensor array (MFDA), inertial navigation and control system (Balefire), the HAUV-1000 (Dolores), subsea data acquisition system, ship-based GPS to provide global position information, and a USBL positioning system. The HAUV was configured with the MFDA coil such that the coil is visible in the camera by the pilot. The sensor electronics pressure vessel was installed in the forward instrument bay on the HAUV. The HAUV was deployed trim and neutral for operation in nominal seawater for our study area and site conditions (salinity and temperature).

Unless the ROV speed was the variable being tested, the mission control and/or ROV operator attempted to maintain a speed of approximately 1 knot (~0.5 m/s) resulting in approximately 5 cm along-track sampling by the MFDA (operating at 10 Hz). Data are stored locally on the topside “copilot” control computer.

The host vessel is an 84-foot aluminum "swiftship" that has been modified for salvage/dive operations and dedicated ROV surveying. It contains a 3-anchor mooring system with hydraulic winches and a 2-ton marine crane and smaller davits for operations. The host vessel has a Trimble SPS461 dual receiver GPS system permanently installed and dedicated to the HAUV system. This GPS and heading receiver is DGPS capable and utilizes L1/L2 carrier GPS, Satellite-Based Augmentation System (SBAS), Minimum Shift Keying (MSK) beaconing, and OmniSTAR receivers for 25 cm horizontal accuracy and 50 cm vertical accuracy as quoted on the manufacturer specification documents. With the dual antenna solution, differential corrections provide a heading accuracy of 0.05 degrees RMS.

5.4 DATA COLLECTION PROCEDURES

The data required for creation of the metrics detailed in Section 3 are raw EMI data, raw navigation sensor data, and the processed navigation solution. These data types are time-stamped and logged in the topside data acquisition computer during testing. During surveys, we also performed calibrations to check our navigational and positioning system functionality and accuracy. Two ISO targets, separated by 5 m and contained in the survey line between spar buoys, were used to calibrate the EMI array and navigation and positioning system at the beginning and end of each data collection day.

Over the course of the demonstration, a total of 4,316 linear meters were surveyed, with an average sample distance of 3.35 cm. During data collection, several QC procedures were utilized:

1) The topside computer acquiring the raw EMI data printed messages to the computer’s console every time a sample was acquired. The constant movement of these messages assured regular receipt of EMI array data.

2) A color-coded waterfall plot displaying the sum of the I and Q values across the four frequencies was projected on the topside ROV control GUI.

3) Data logged by the topside ROV control GUI was periodically checked using software QA routines. Checks included sample distance metrics and I and Q noise metrics for each coil and frequency.

Once the sensor is calibrated, a noise cancellation procedure can be conducted to allow the sensor to automatically search through a number of frequency sets and select the set that is not affected by any external electromagnetic interference. In addition, the sensor is "zeroed" to achieve a stable in-air absolute calibration. Periodically throughout each data collection day, the EMI array data was processed to assure data quality. In addition, the real-time navigation display flashes indicators if data quality of any sensor is not met, including loss of bottom-lock by the DVL.

To continuously monitor properties of the water column during tests, we mounted a small marine-grade conductivity, salinity, and temperature (CST) logger to the ROV. Observed conductivities were between 3.1 and 3.8 S/m during the demonstration period. Temperature remained relatively constant during tests, with only some small perturbations (< 3 degrees Fahrenheit) during changes in the tidal current.

6.0 ANALYSIS AND DATA PRODUCTS

Data analysis was performed using a custom preprocessing, detection, and target characterization software environment.

6.1 DATA PREPROCESSING

The preprocessing of ROV-based EMI data includes median filtering of each in-phase (I) and quadrature (Q) data channel to remove intermittent spikes found in the raw data. To remove the drift, the data are sent through a detrending algorithm prior to detection processing.

6.2 TARGET SELECTION FOR DETECTION

The detection signal is the sum of the I and Q values across one or more frequencies following data preprocessing. A threshold is applied to this statistic to produce target detections. Historic data collected using the sensor and data collected during preliminary tests in Florida, Massachusetts (test stand data), and North Carolina were used to set detection thresholds. A baseline SNR detection threshold was set to 9 dB based on statistical estimation of a non-fluctuating target in Gaussian noise at an operating point associated with a relatively conservative 0.01 probability of false alarm.

6.3 PARAMETER ESTIMATION

For each detection, an estimated corresponding position is determined using a custom algorithm that searches for the zero crossing between the bipolar response typically produced by the quadrapole receiver coils. The location corresponding to the zero crossing is the estimated location of the target.

6.4 TRAINING / DISCRIMINATION

Although our demonstration did not explicitly endeavor to assess the discrimination potential of this ROV-based EM system, we did investigate a preliminary version of a polarizability inversion methodology using MFDA array data. Utilizing only the angular offset with the single axis transmitter of the MFDA, we configured our inversion algorithm to extract target polarizabilities. An example result of our polarizability inversion is shown in Figure 6**Error! Reference source not found.** for a 3-inch steel sphere.

Classification features are extracted from the forward model realization most closely matching the observed data. Multiple data points are concatenated together and used in the inversion to generate the frequency-domain polarizabilities. This was required to facilitate angular illumination and consequently constrain the axial moments of the target, so as to produce representative polarizability values.

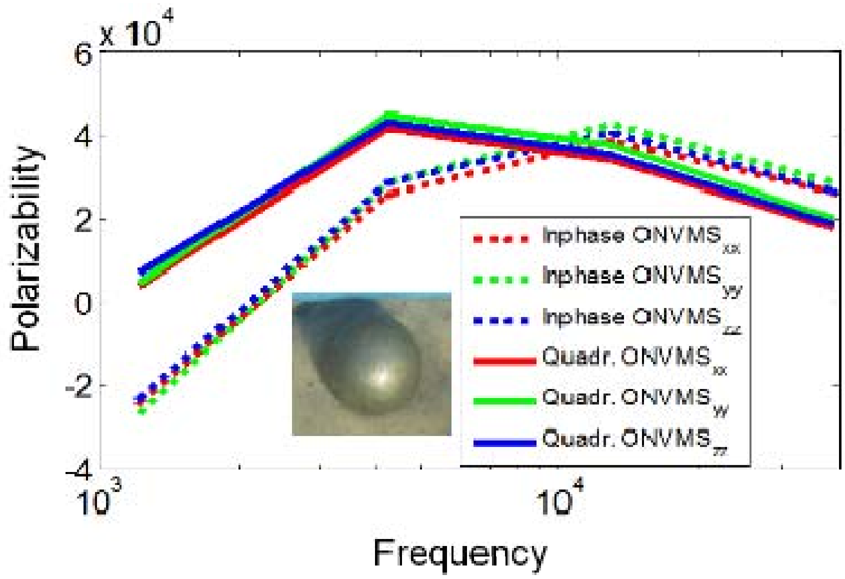


Figure 6. Example of Frequency-domain Inverted Polarizabilities Using the Ortho-normalized Volume Magnetic Source Model that Was Modified to Address EM Propagation through a Conductive Seawater Medium.

This example shows that nearly identical axial polarizabilities for both In-Phase and Quad-Phase components are derived as expected for the axi-symmetric sphere target tested.

6.5 DATA PRODUCT SPECIFICATION

Data products consist of calculated metrics as well as figures to illustrate the data used to calculate each metric. These are represented by plots of time versus the navigation system data and time versus the ground truth data or desired data. For altitude (bottom-following) data the navigation output was compared to the desired height above seafloor. The estimated detection location (N, E) were compared to the ground truth location of the target interrogated. Halos of different sizes were used to illustrate localization accuracy and precision.

7.0 PERFORMANCE ASSESSMENT

We assessed performance using the previously defined test objectives and associated metrics shown in Table 2. These include quantitative metrics related to navigation and control and detection/localization, as well as qualitative metrics such as those associated with launch and recovery (LAR) and ease of use. An assessment of each objective is provided in Table 2.

Table 2. Summary of Target Objectives, Metrics, and Results.

Performance Objective	Target Metric	Result
Bottom Following (successfully achieved)	$\Delta A < 0.15$ m $\sigma A < 0.15$ m	$\Delta A = 0.1$ m $\sigma A = 0.03$ m
Station Keeping Accuracy and Precision (successfully achieved)	ΔN and $\Delta E < 0.35$ m σN and $\sigma E < 0.35$ m $\Delta A < 0.15$ m $\sigma A < 0.15$ m $\Delta H < 1$ degree $\sigma H < 2$ degree $\Delta R < 1$ degree $\sigma R < 2$ degree $\Delta P < 1$ degree $\sigma P < 2$ degree	$\Delta N = 0.13$ m, $\Delta E = 0.12$ m $\sigma N = 0.07$ m, $\sigma E = 0.06$ m $\Delta A = 0.03$ m $\sigma A = 0.01$m $\Delta H = 0.86$ degree $\sigma H = 0.61$ degree $\Delta R = 0.31$ degree $\sigma R = 0.08$ degree $\Delta P = 0.27$ degree $\sigma P = 0.09$ degree
Waypoint Mission Control (successfully achieved)	$\Delta D = (\Delta N^2 + \Delta E^2)^{0.5}$ $\Delta D < 1.5\%$ distance travelled $\sigma D < 0.5$ m	$\Delta D_{waypoint} = 0.26$ m $\sigma D_{waypoint} = 0.29$ m $\Delta D_{line} = 0.7$ m $\sigma D_{line} = 0.53$ m Typical Distance traveled approx. 40 m; $\%\Delta D_{waypoint} = 0.65\%$ $\%\Delta D_{line} = 1.75\%$
Detection of all munitions greater than 60 mm (successfully achieved)	SNR > 9 dB Pd > 0.95 (assuming a nonfluctuating target and Gaussian noise a 0.95 Pd at 9 dB corresponds to a pFA of approximately 0.01)	All target SNRs > 20.7 dB Pd = 1.0
Detection Location Accuracy and Precision (successfully achieved)	ΔTN and $\Delta TE < 1.0$ m σTN and $\sigma TE < 1.0$ m	$\Delta TN = 0.29$ m $\Delta TE = 0.22$ m $\sigma TN = 0.42$ m $\sigma TE = 0.51$ m
Ease of use (effective with some limitations)	Ease of use comparable to alternate standard marine surveying procedures	ROV control and navigation GUI very user friendly. Lack of real-time fusion of USBL position with INS/DVL position made true ROV location difficult to determine within GUI. Procedures put in place to minimize error between USBL and DVL/INS position.
Mission Assisted Autonomy (effective)	Value of assisted autonomy functions	Very valuable especially during line following operations. Auto-heading, auto-depth, and auto-velocity critical during line following operations.
Integrated System Stability (effective with some limitations)	Valuation of time and effort to stabilize	Integrate EM / ROV system stabilized in less than 30 minutes using 1 or 2 lb dive weights

7.1 BOTTOM FOLLOWING

Bottom following capability was assessed by analyzing navigation and control observations for traverses of the ROV-EM system between prescribed waypoints. Images of the HAUV captured during bottom following tests are shown in Figure 7.

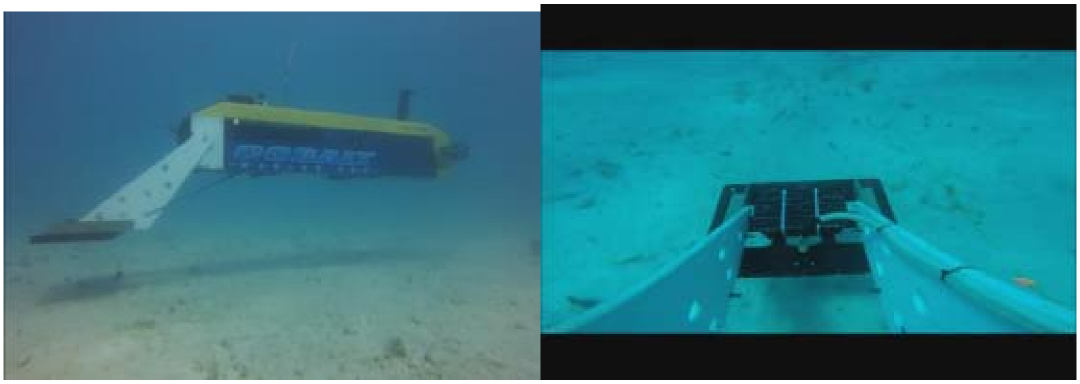


Figure 7. Still Shots of the Integrated ROV-EM System (left) and the EM Sensor (right) Performing Bottom Following Operations.

The average altitude error over 18 transects, each of which was approximately 50 m in length (total distance approximately 900 m), was 10 cm, while the standard deviation of the altitude was 3 cm. These metrics were lower than the average and standard deviation objectives of 15 cm and 15 cm, respectively. Figure 8**Error! Reference source not found.** shows the desired versus actual altitude, roll, and pitch data collected during one of the transects.

Achieving the bottom, keeping objectives, and maintaining roll and pitch errors, less than half a degree indicates vehicle stability sufficient for near-bottom (< 0.5 m) surveys. An average forward pitch error of 0.29 degrees was confirmed using underwater pictures of the vehicle taken by divers while the vehicle was in motion. Midwater tests of the vehicle at higher speeds showed a tendency of the vehicle to dive with increased speed. Possible contributors to the pitch error include current, tether drag, and downward force imparted on the vehicle when in motion due to the mounting of the EMI sensor forward and underneath the vehicle.

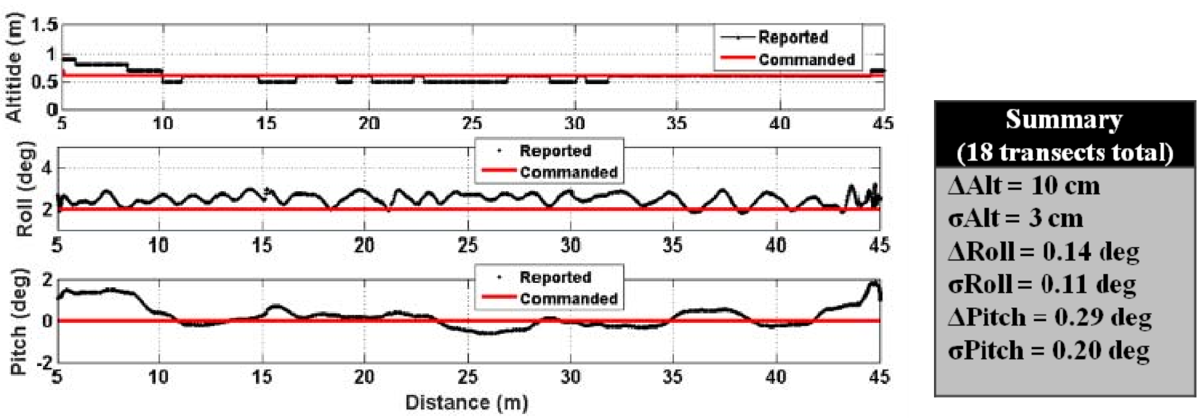
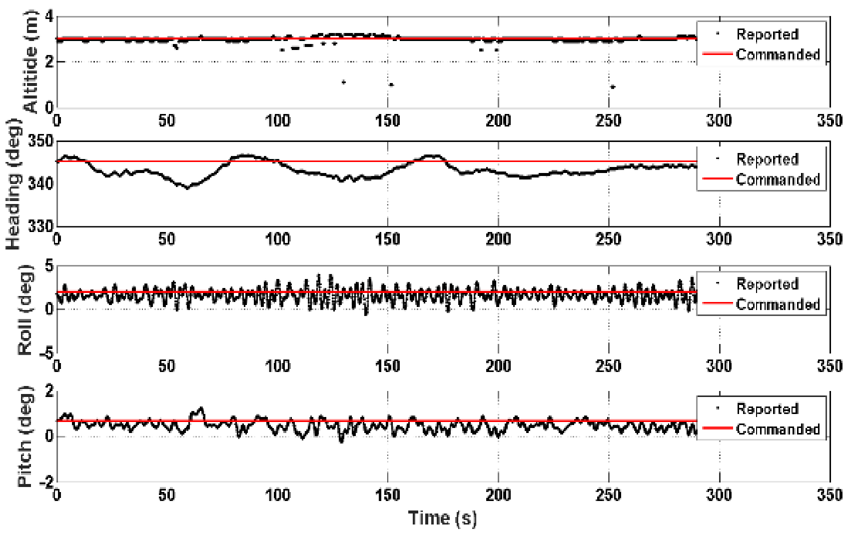


Figure 8. Plots Showing Desired versus Actual ROV Altitude, Roll, and Pitch during a 45 m Transect.

7.2 STATION KEEPING

Station-keeping objectives focused on maintaining position of the sensor array over a commanded location, in our case over an individual target in the deployed target grid or over a grid corner marker. Our objective was to stay, on average, within 35 cm of the commanded northing and easting coordinates. We commanded the ROV-EM system to maintain position for periods between one and five minutes over several target items to provide data for calculating station-keeping metrics. Examples of data collected from one of the station-keeping data collections are shown in Figure 9. All of the stated station-keeping objectives were achieved.



Summary (13 stations)

ΔE, ΔN = 12 cm, 13 cm
σE, σN = 5.7 cm, 6.7 cm

ΔAlt = 2.5 cm
σAlt = 1.3 cm

ΔYaw = 0.86 deg
σYaw = 0.61 deg

ΔRoll = 0.31 deg
σRoll = 0.08 deg

ΔPitch = 0.27 deg
σPitch = 0.09 deg

Figure 9. Example of Station-keeping Data Collected while Keeping Station for 5 Minutes over an Individual Target.

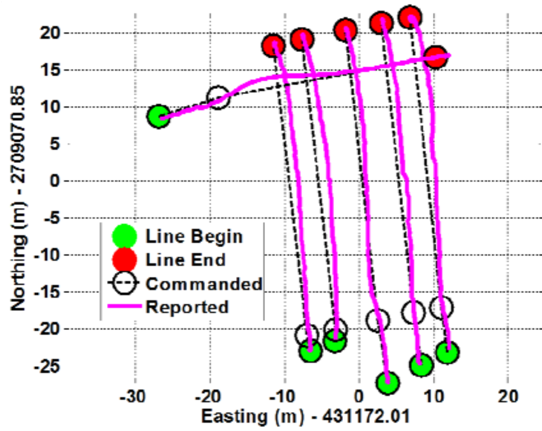
Data zoom-in plots show the local position error found by subtracting the commanded northing and easting position from the northing and easting position reported by the navigation system.

7.3 WAYPOINT CONTROL

The ROV-EM system was tested on its ability to transit from one point to another and follow a given line. The operator can preplan and load mission control waypoints in the user interface software. The stated metric was to achieve distance errors less than 1.5 percent distance traveled. Average northing and easting error is defined as the mean of reported position minus the nearest desired position. The waypoint error indicates how accurately the ROV's final position was to the desired waypoint. The line error indicates how accurate the ROV followed the line between the two waypoints. Table 3 contains the measured performance of the waypoint and line-following behaviors.

Table 3. Waypoint and Line Following Performance in Meters.

Metric	Waypoint	Line
ΔD (m)	0.26	0.7
σD (m)	0.29	0.53
ΔN (m)	0.15	0.13
σN (m)	0.23	0.16
ΔE (m)	0.04	0.62
σE (m)	0.28	0.59



The waypoint errors were less than the line errors indicating the navigation and control system's ability to maneuver to a specified waypoint. Line error metrics, specifically the ΔE value of 0.62 m, indicate the ROV was more than 60 cm from the desired line for the majority of the time spent performing the coverage transects. This is to be expected since the version of the navigation and control software used during this demonstration contained control feedback specific to reaching the next waypoint and did not have a true line-following capability, i.e., no control feedback existed to maintain the ROV's proximity to the line. Even without a true line-following capability, the consistent ROV location offset from each line when heading north makes full coverage of the target area feasible. The summary performance of the waypoint navigation control as a function of approximate distance travelled reveals that the waypoint accuracy was within 0.65% distance travelled and the line following was approximately 1.75% distance travelled.

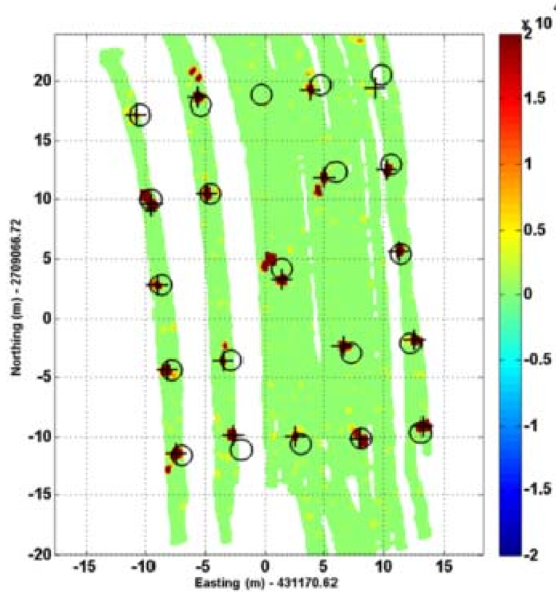
7.4 DETECTION METRICS AND LOCALIZATION ACCURACY

Detection metrics were calculated using the SNR and location of detections output from the detection processing and ground truth information. The target detection objective was target SNR greater than 9 dB for all targets greater than 60 mm in size. We achieved the objective with SNR greater than 20.7 dB for all targets including data from sensor altitudes between 20 cm and 60 cm. The largest detection SNR value was 84 dB for the large ISO and the smallest was 20.7 dB for the 60 mm mortar.

Detections were scored as TOI detections if the detection location was within a radius of 1.5 m of the TOI ground truth location. Table 4 shows the SNR and offset from the estimated target location to the ground truth location for all of the TOI.

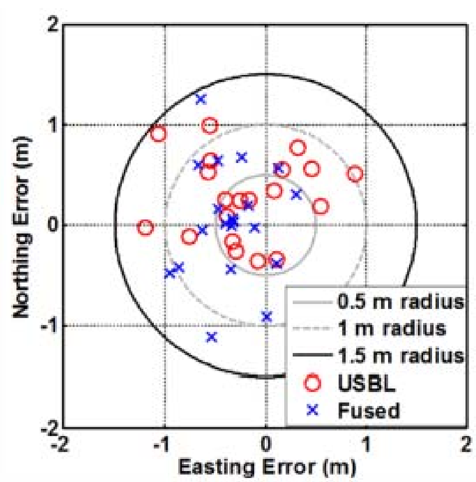
Table 4. Detection Performance Results.

ID	Target	Detected?	SNR (dB)	Offset (m)
1	60 mm	Detect	20.7	1.23
2	81 mm	Detect	22.1	0.56
3	Large ISO	Detect	83.6	0.26
4	81 mm	Detect	65.9	0.43
5	81 mm	Detect	54.1	0.58
6	81 mm	Detect	60.4	0.12
7	Medium ISO	Detect	38.5	0.80
9	81 mm	Detect	37.5	0.50
10	Medium ISO	Detect	48.1	0.40
12	Large ISO	Detect	76.9	0.40
13	60 mm	Detect	25.7	0.33
14	Medium ISO	Detect	38.3	0.71
17	105 mm	Detect	25.8	1.07
18	155 mm	Detect	61.6	0.91
19	90 mm	Detect	33.4	0.37
20	3" Round	Detect	52.6	0.90
21	105 mm	Detect	69.5	0.32



We calculated two estimates of ROV location. The first estimate was based on USBL data only. The second estimate fused USBL and INS data. USBL and USBL/INS-fused detection location accuracy metrics are compared in Table 5. Overall the USBL and Fused approaches yielded similar results, with an average offset of 0.67 m and 0.66 m, respectively. The localization error summary indicates a slight bias offset toward the northwest.

Table 5. USBL and Fused detection location accuracy metrics



	USBL	Fused
ΔR (m)	0.67	0.66
ΔN (m)	0.29	-0.03
σN (m)	0.42	0.56
ΔE (m)	-0.22	-0.35
σE (m)	0.51	0.33

Overall, the performance objective of mean and standard deviation of easting and northing estimates less than 1 m was achieved. Retrospective analysis revealed that heading errors from the INS data were likely the largest factor affecting the overall localization accuracy. Other sources of error included those from the ship GPS, those associated with USBL range and bearing accuracy, across-track resolution of the EM receivers, and errors in the actual ground truth locations.

7.5 INTEGRATED SYSTEM STABILITY

The integrated system proved to be very stable in the water. Initial trimming of the system took approximately 30 minutes and consisted of adding 1 and 2 lb dive weights to the platform to make it level in the water. After system deployment, bubbles were released from under the system by a diver manually rocking the system back and forth on the water surface. This was all that was required after deployment in the water to permit operations.

7.6 OPERATIONAL EASE OF USE

We found that even with the smallest mini-ROV systems, launch and recovery (LAR) will likely require some small davit to support sea-based deployment. We determined the ease of use of the system by overseeing and reviewing ROV-EM operations including system deployment, recovery, and data collection. The Dolores HAUV weighs over 500 pounds in air and thus requires a hoist for LAR and sufficient deck space for storage and maintenance. Since most of the system components are commercially available or otherwise supported line-replaceable units, the overall system has a great deal of modularity. The following personnel are required for ROV-EM operation using the Dolores platform and MFDA EMI sensor: 1) ROV pilot, 2) Co-pilot to assist in sensor monitoring and data logging, and 3) a minimum of one person to monitor the tether and aid in deployment and recovery of the ROV-EM platform. The pilot planned missions and performed command and control of the ROV through the pilot user interface (UI). This interface has a number of features for planning missions; viewing and controlling the ROV configuration; creating real-time event markers (aka, Man Over Board); logging and playing back system data; displaying and logging EM data and sonar data; and controlling the ROV subsystems, such as thrusters, lights, cameras, sonar systems, and other auxiliary sensors. We developed a Standard Operating Procedure (SOP) and QuickStart guide for operational users conducting geophysical surveys with the system. The guidance documentation is meant to provide single button access to run EMI array command and control and data acquisition when performing marine operations with the integrated ROV-EM system. The combination of the SOP documentation, software executables, and associated software QuickStart guides successfully enabled non-expert operators to acquire data with the system without White River Technologies' expert users and analysts on site. This has resulted in over 900 hours of operations with the ROV-EM system without expert technical staff onboard the host vessel and represents the potential for transition of the technology to operational application.

The assisted autonomy objective was to determine the improvements in the execution of ROV-EM applications using automated ROV behaviors such as altitude, heading, bottom following, station keeping, and waypoint navigation. Autonomous behaviors were critical to efficient calibration and operation of the ROV-EM system. Manual attempts at controlling ROV altitude, heading, and line following resulted in lower quality data, requiring additional time compared to autonomous data collections. The additional time was due to abandoning numerous transects due to observed drifts in sensor altitude and drifting position from the desired altitude and line position.

8.0 COST ASSESSMENT

8.1 COST MODEL

The cost elements that were tracked during the demonstration in Florida are detailed in Table 6. The provided cost elements are based on a simple and incomplete cost model developed for the Dolores HAUV-1000-based ROV-EM system used in our demonstrations. The integrated ROV-EM system does not yet have a price developed for purchase or lease. Therefore, some aspects of the price elements must be estimated for the purposes of cost assessment.

Table 6. Cost Model for a Detection/Discrimination Survey Technology

Cost Element	Data Tracked	Estimated Costs
Instrument cost	N/A (See description below)	Estimated costs of the marine EMI array are $150/day or $750/wk
Support equipment lease rates	Lease rates for major components • Engineering estimates based on current development • Lifetime estimate • Consumables and repairs	Vessel Charter: $ 8,400/wk HAUV w/ Operator: $ 4,500/wk EM array and NCS: $ 1,200/wk USBL: $ 700/wk RTK-GPS: $ 1,200/wk
Mobilization and demobilization	Cost to mobilize to site • Derived from demonstration costs	Equipment Prep (est.): $ 950 Shipping (NH-FL-NH): $ 3,810 ***TOTAL Mob/Demob: $ 4,760***
Site preparation	Time and cost to setup test site (relates to seafloor IVS set up)	Test Target Prep: $ 550 Dive Ops Site Prep: $ 4,550
Instrument setup costs	Unit: $ cost to set up and calibrate Data requirements:	ROV Control Setup: $ 1,525 EM Array Setup/QA: $ 275 RTK-GPS Setup: $ 175 ***TOTAL Setup: $ 1,975***
Survey costs	Unit: $ cost per acre Data requirements: • Hours per acre • Personnel required	1.1 acres/hour at 100% coverage 100% coverage ($/acre): $ 571 50% coverage ($/acre): $ 286 25% coverage ($/acre): $ 143
Detection data processing costs	Unit: $ per hectare as function of anomaly density Data Requirements: • Time required • Fixed costs and Personnel required	Fixed Costs: $ 1,250 1 person (analyst at $100/hr) 2 mins. / anomaly (average) Per anomaly (100/acre): $ 3.33 Per acre (100/acre): $ 333

Remotely-operated vehicles vary in size, power, payload capacity, and sensor integration capability. For ROV-EM operation, the size and power of small inspection-class vehicles such as the Seabotix vLBV ROV is the minimum required. Larger inspection and midsize class ROVs (e.g., Saab Seaeye Falcon, Teledyne Stingray) that provide more power but remain deployable using a davit and not requiring other specialized launch and recovery equipment are also appropriate for ROV-EM operation. We found these systems lease for between $3,500 and $5,300 per week (or may be procured for $100K-$220K).

Support equipment such DVL/IMU positioning, RTK-GPS, vessel, and environmental monitoring instrumentation have associated lease rates that were tracked independently (Table 7).

This equipment is categorized as preferred, required, or not needed for UXO operations. All associated labor costs were tracked and aggregated to form the cost element assessment.

Table 7. Estimated Support Equipment Costs

Equipment	Lease cost	Purchase Cost	Category
RTK-GPS	$1,200 per week	$40k	Required
USBL	$700 per week	$22-200k	Preferred
Vessel	$8,400 per week	N/A	Required
DVL/IMU	$1,400 per week	$29,200	Required

We estimate the total cost to mobilize the system, inclusive of shipment via commercial carrier for our demonstration, to be approximately $4,760. The total labor and materials cost estimated for preparation of the system for mobilization is $4,950. The breakdown of shipping costs yielded $3,810 for shipping to and from the demonstration site. We obtained a quote for $75/hour from a local dive crew to estimate the anticipated dive crew costs. This $6,000 weekly cost is for a two-person (non-EOD-trained) dive team that is used for calibration target deployment and setup of other underwater infrastructure. Configuration, setup, and checkout of the RTK-GPS system will take approximately two hours. Overall, this results in an estimated instrument setup cost of $5,100.

Based on estimates from the testing reported in this document, 100% area coverage will cost $571 per acre, 50% area coverage will cost $286 per acre, and 25% coverage will cost $143 per acre. Our estimate for data processing costs are $333 per acre, assuming approximately 100 anomalies per acre.

9.0 IMPLEMENTATION PROSPECTUS

The overarching goal of this demonstration project was to evaluate innovative technologies required for deploying underwater EMI sensors from ROVs to overcome limitations of current diver-deployed, towed, and unmanned integrated underwater UXO detection systems. The demonstration we conducted was the first that we know of in which a full marinized multisensor EM array was tightly integrated with a HAUV system capable of controlled maneuvers close to the seafloor. Despite the preliminary nature of our assessment, we were able to evaluate the prospects and potential challenges for directly transitioning and implementing the system and related procedures for operational use in MMRP production environments.

Our demonstration sought to assess three primary types of survey activities that are relevant to underwater UXO detection and remediation operations: 1) Local Area Search Missions to detect, locate, and digitally mark UXO on or beneath the seafloor within a predefined munitions response area, 2) Anomaly Characterization to provide high resolution (i.e., full coverage) mapping, target localization, and potential classification analysis (via dynamic one-pass classification methods), and 3) Reacquisition and Cued Classification Surveying to acquire stationary target confirmation and/or classification data for dig/no-dig assessment (Figure).

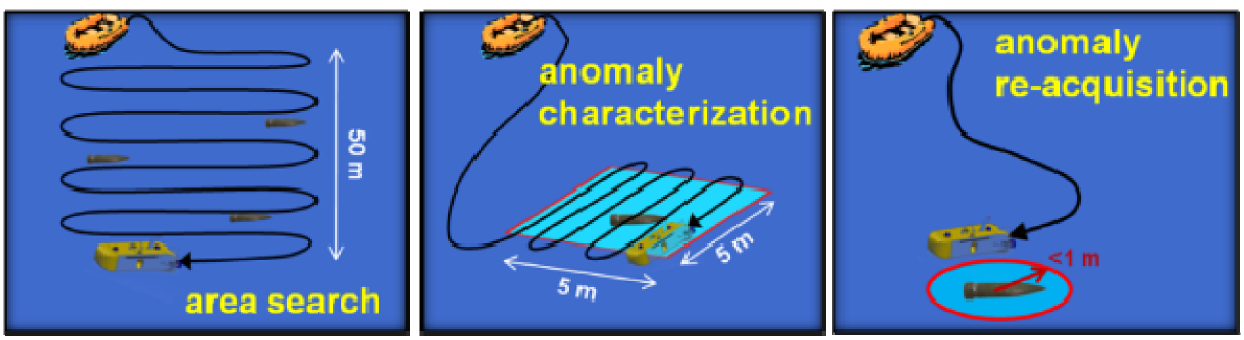


Figure 10. Survey Activities Relevant to Underwater UXO Detection Include Local Area Search (left), Anomaly Characterization (center), and Anomaly Reacquisition (right).

9.1 LOCAL AREA SEARCH MISSIONS

Local area search missions include continuous mapping over areas of the seafloor on the order of 2000 to 10,000 m^2 (0.5 to 2.5 acres) for a given surface vessel anchoring site. For our demonstration, we limited surveys to our grid area, which was 30 m x 40 m or 1600 m^2 (0.4 acres). Local search areas of this size are constrained by the range of the ROV system (typically 100-500 m) and degradation of positioning accuracy with range from the surface deployment vessel. These range-dependent local positioning accuracy issues appear to dominate the overall performance of the ROV-EM system. Overall the ROV-based EM technology we demonstrated was ***generally effective*** for local area search missions with clear limitations and associated opportunities for operational improvement.

A clear limitation of the ROV-EM system we demonstrated in terms of survey coverage efficiency is due to the limited size of the EM sensor array used. Full coverage over a site requires 1 transect every 50 cm. Therefore, at an estimated 1 knot (0.51 m/s), our estimated survey coverage efficiency is approximately 4.4 hours per acre (requiring 8192 m of linear line transect surveying). Including turnaround time and daily IVS and related QA checks, this is equivalent to approximately 1.5-2 acres per day. The survey efficiency simply scales linearly with array survey coverage swath width or areal coverage planned. Thus, an array 2 m wide would likely cut the current survey time in half and increase the production rate to 3-4 acres per day. Commensurately, a 50% coverage requirement would result in the same areal coverage efficiency. This assumes best case conditions; hydrodynamics and site/survey complexity may degrade maneuverability, survey production efficiency, and correspondingly, coverage rates.

9.2 ANOMALY CHARACTERIZATION

Anomaly characterization over relatively small areas of the seafloor may be useful to conduct when the ROV-EM system is cued to the area by previous surveys or other information (e.g., wide area magnetometer mapping or acoustic mapping survey data). In this case, the ROV-EM operator may wish to survey at high resolution over a limited area on the order of 10-50 m^2 (5m x 5m area, for example). This type of close-in high-resolution surveying requires lateral and vertical control that is accurate and precise enough to produce densely sampled data. This type of survey mission may ultimately be used for dynamic classification data acquisition and thus must have the control and stability to acquire data for inversions. Because of the stability of the platform and associated ability to acquire relatively high SNR data over small areas, we found the overall anomaly characterization application to be ***very effective*** for ROV-based EM. The point-to-point relative position accuracy appears to be good enough over these small areas to perform dynamic or multipoint inversion to aid in characterizing and discriminating targets. This may provide a useful mechanism for future dynamic classification methods for marine UXO.

9.3 RE-ACQUISITION AND CUED CLASSIFICATION

Reacquisition surveys based on predefined coordinates may be important for visual inspection, marking, detailed confirmation data collection with EM, sonar, or a combination of them, as well as for potential static cued data collections for advanced classification data collection. The ROV-EM system may also be utilized in reacquisition surveys in collaboration with other ROV-based systems to guide them to a location for remediation operations. For this mission, the ROV-EM system we demonstrated was ***generally effective*** but had limitations associated with navigation and positioning accuracy that increase with range in the case of inertial navigation, with or without USBL integrated. Overall, the reacquisition capability allowed for anomalies to be localized to within an approximate one meter circular error probability. Furthermore, the station-keeping control capability was very effective at holding position to within ~25cm over a target position for minutes at a time in low to moderate current conditions. Some adjustments may be required and degradation experienced in current conditions exceeding the maximum 1.8 knot currents we experienced during our demonstration. The MFDA array we used is not configured for classification due to its inability to produce multi-angle EM excitation and effectively elucidate all three components of the magnetic polarizability of targets under the array.

9.4 SUMMARY OF IMPROVEMENTS

To make the system more effective for underwater munitions surveying, a number of improvements are recommended. Amongst the most important improvements is the development and implementation of a tailored yet low cost shallow-water positioning system that is capable of augmenting or replacing the USBL- or inertial-only solutions we demonstrated. Another approach to improving the positioning and control capability of the ROV-based EM system is to implement effective fusion methods that combine the available positioning methods and optimize the use of the position and orientation information in varying water depth and bottom conditions. We also suggest the use of seafloor calibration points to mitigate inertial drift. These methods should improve the overall survey accuracy and effectiveness – especially as survey areas grow larger than one acre. To improve the survey coverage rate, we suggest integration of wider EM array from the HAUV. This must be balanced by improved hydrodynamic design that reduces the overall drag area of the array by creating more open/flooded frame components. Efforts to develop arrays both 1.6 and 2.1 meters wide are underway, and retrofitting/testing is planned for the 2016/2017 timeframe.

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